

Modelling Greenland Outlet Glaciers

Final Report for NAG5-8632

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FINAL REPORT: MODELLING GREENLAND OUTLET GLACIERS

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The objective of this project was to develop simple yet realistic models of Greenland outlet glaciers to better understand ongoing changes and to identify possible causes for these changes.

Several approaches can be taken to evaluate the interaction between climate forcing and ice dynamics, and the consequent ice-sheet response, which may involve changes in flow style. To evaluate the ice-sheet response to mass-balance forcing, Van der Veen (*Journal of Geophysical Research*, in press) makes the assumption that this response can be considered a perturbation on the reference state and may be evaluated separately from how this reference state evolves over time.

Mass-balance forcing has an immediate effect on the ice sheet. Initially, the rate of thickness change as compared to the reference state equals the perturbation in snowfall or ablation. If the forcing persists, the ice sheet responds dynamically, adjusting the rate at which ice is evacuated from the interior to the margins, to achieve a new equilibrium. For large ice sheets, this dynamic adjustment may last for thousands of years, with the magnitude of change decreasing steadily over time as a new equilibrium is approached. This response can be described using kinematic wave theory. This theory, modified to pertain to Greenland drainage basins, was used to evaluate possible ice-sheet responses to perturbations in surface mass balance. The reference state is defined based on measurements along the central flowline of Petermann Glacier in north-west Greenland, and perturbations on this state considered. The advantage of this approach is that the particulars of the dynamical flow regime need not be explicitly known but are incorporated through the parameterization of the reference ice flux or longitudinal velocity profile.

The results of the kinematic wave model indicate that significant rates of thickness change can occur immediately after the prescribed change in surface mass balance but adjustments in flow rapidly diminish these rates to a few cm/yr at most. The time scale for adjustment is of the order of a thousand years or so.

This result suggests that, if the observed ongoing thickness changes on the Greenland Ice Sheet are in response to changes in surface mass balance, it may be expected that the rates of thickness change will decrease over the next few years. However, there is no supporting climatological evidence for important changes in snowfall and/or ablation (sufficiently large to lead to thickness changes of the observed magnitudes). Van der Veen (in press) concludes that, in all likelihood, the ice sheet is dynamically adjusting to other forcings, which may include internal instabilities.

Implicitly, in formulating the kinematic wave model, the assumption is made that the perturbations remain sufficiently small so as not to affect the dynamics of the reference state, and rapid switches in flow style are precluded a priori from the analysis. To investigate the Jakobshavn Effect, a model that incorporates longitudinal stress gradients and other sources of flow resistance, is needed. The Jakobshavn Effect is believed to be initiated by increased calving from the floating outlet glaciers. Thus, a first step in studying this instability mechanism is to assess how large calving events affect the flow upglacier and, in particular, whether such an event leads to increased stretching. The next step is to evaluate how any perturbations originating on the floating portion are transmitted across the grounding line and what the possible consequences for drainage from the interior may be. This further modelling is the main objective of the continuing project NAG5-10978.

To better understand fracturing and iceberg calving, a review of observations is presented by Van der Veen (1999; published in 2000) and Van der Veen (Progress in Physical Geography, in press). Observations on crevasse orientation relative to principal stress or strain rate shows that in many instances, crevasses are not aligned in the optimum direction perpendicular to the direction of principal tensile stress. Moreover, a number of studies report the occurrence of strike-slip motion, with the crevasse walls moving parallel to each other. These observations cannot be explained by the conventional model for crevasse formation, introduced over a century ago by William Hopkins. Instead, Van der Veen (1999) proposes that crevasses are the manifestation of mixed-mode fracturing, combining the opening mode usually associated with crevassing, with the shearing mode, which is equivalent to strike-slip faulting. In a biaxial crevasse field, the crevasse will tend to orient itself in the optimum direction, thus minimizing the shearing motion, but this direction is achieved asymptotically. This means that on glaciers subject to tension and lateral shear, the orientation of crevasses may differ by up to 20° from the optimum direction. Further, by incorporating the shearing mode, the depth to which fractures can penetrate may be significantly larger than for the opening mode. The weight-induced lithostatic stress increases with depth below the surface, so that at some depth, the walls of a crevasse cannot physically

separate. However, it is possible that the shearing mode acts over greater depths, thus allowing the fracture to penetrate deeper without separation of the fracture surfaces. This might explain why, on some glaciers, crevasse traces persist well into the ablation area, where surface melting should have obliterated all visible traces of crevasses formed upglacier, if these crevasses penetrated only a few tens of meters, as predicted for the opening mode.

Based on a review of observations on different types of calving glaciers, Van der Veen (Progress in Physical Geography, in press) proposes a simple calving model. Glaciers that exist in a sufficiently cold climate can form floating ice shelves and ice tongues that typically do not extend beyond confinements such as lateral fjord walls or mountains, and ice rises. If the local climate exceeds the thermal limit of ice shelf viability, as is the case for temperate glaciers, no floating tongue can be maintained and the position of the terminus is determined by the thickness in excess of floatation. If the snout is sufficiently thick, a stable terminus position at the mouth of the confining fjord – usually marked by a terminal shoal – can be maintained. Further advance is not possible because of increasing sea-floor depth and diverging flow resulting from lack of lateral constraints. If a mass balance deficiency causes the terminal region to thin, retreat is initiated with the calving front retreating to where the thickness is slightly in excess of floatation. In that case, the calving rate is determined by glacier speed and thickness change at the glacier snout. Advance and retreat of the calving front is not driven by changes in calving rate, as in the conventional model, but by flow-induced changes in the geometry of the terminal region. This model is essentially different from prior suggestions in which some empirical relation – most commonly the water-depth model – is used to calculate calving rate and the rate of retreat or advance of the terminus.

Accumulation at the glacier surface is an important forcing for glacier evolution. Van der Veen and others (Journal of Geophysical Research, in press) applied multivariate regression methods to measurements of accumulation covering much of the interior of the Greenland Ice Sheet to evaluate the important factors that describe the current distribution of accumulation. Predictor variables considered in the regression are geographical coordinates and three independent factors describing the geometry of the ice sheet. The results indicate that most of the variance in the data is explained by the combined effect of large-scale atmospheric circulation and ice sheet topography. This finding implies that climate change scenarios in which changes in accumulation are mostly associated with changes in temperature or some other parameter may only be correct if the pattern of atmospheric circulation remains unaltered. Comparison with values predicted with a precipitation retrieval model are favorable, suggesting that the model captures the most important features of Greenland precipitation.

Finally, Van der Veen (Global and Planetary Change, in press) evaluates how well the future contribution of polar ice sheets to global sea level can be predicted. Geophysical models are based on hypotheses that are often derived from theoretical arguments or from observations, or a combination of both. Owing to the open nature of geophysical systems, these models cannot be verified in the sense that it cannot be proven that the model is an accurate representation of the physical reality. At best these models can be confirmed by comparing model predictions against independent observations. The more such observations the model agrees with, the greater confidence can be placed in the model and its reliability as a basis for decision making. A review of mass balance models used to predict past and future contributions to global sea level change arising from changes in snow accumulation and surface ablation on the polar ice sheets is presented by Van der Veen (in press). Observations on which these models are based are ambiguous and there is evidence suggesting that these models do not capture all relevant physical processes, some of which – such as changes in atmospheric circulation patterns – may have an equally important effect on changes in surface mass balance as does the direct temperature forcing. In the context of greenhouse-warming-induced sea level change, uncertainties in model parameters are sufficiently great to yield a range of projected contributions from Greenland and Antarctica that encompass sea-level lowering and rise in 2100 A.D. for each of the warming scenarios considered. The uncertainty associated with ice sheet mass balance parameterizations is of similar magnitude as that associated with temperature projections.

Publications:

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